INVESTIGATION OF EXCITED LEVELS OF ^{6}Li NUCLEUS FROM THE THREE-PARTICLE ^{3}H(α, dα)n REACTION

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In the kinematically complete experiment with the use of a beam of α-particles with an energy of 67.2 MeV and a titanium-tritium target, the three-particle ^{3}H(α, dα)n reaction is investigated. In the upper branches of the d—α coincidence loci obtained for the pairs of the registration angles of deuterons and α-particles, 15° — 15°; 27.5° — 15°; and 21° — 15°, three excited levels of ^{6}Li nucleus with excitation energy from 7 to 14 MeV are observed. It is assumed that the process is sequential. On its first step, the unstable levels of nucleus ^{6}Li are formed, which decay then into $d + \alpha$. The fitting gave the energy positions $E_{\rm exc}$ = 8.81(0.13); 11.31(0.38); 13.51(0.38) MeV and widths Γ = 1.84(0.71); 1.28(1.09); 1.45(1.52) MeV, respectively, for the three resonance levels observed in the experiment.

Because ^{6}Li nucleus is one of the lightest nuclei with a peculiar cluster structure of the ground and excited states, it is the object of intense experimental and theoretical investigations during last decades. We consider that cluster levels are situated near the energies of the decay of a nucleus into the corresponding clusters, and the threshold of the decay into an α-particle and a deuteron differs greatly from the nearest threshold of the decay into t+^{3}He. In this case, the scheme of the levels of ^{6}Li nucleus [1] should include a stateless zone from 6 to 16 MeV [2]. At the same time, the results of numerous theoretical investigations based on different approaches [3 — 7] foretell the existence of several excited levels lower than the threshold of the decay into t+^{3}He. However, there are few experimental confirmations of the existence of such states. For example, the analysis of the inclusive spectrum of α-particles from the ^{9}Be(p, α)^{6}Li reaction, which was obtained by using the 30-MeV beam of protons, revealed an anomaly near the excitation energy of ^{6}Li nucleus, 8 — 12 MeV, which can be explained by the occupancy of one or some levels of ^{6}Li [8]. One more argument in favour of the existence of excited states in this energy range is given by results of the R-matrix analysis of elastic α − d scattering carried out in [9], where the broad levels of ^{6}Li nucleus with excitation energies of 14 and 15.8 MeV were discovered. The excited levels with $E^* = 14.5$ and 16 MeV and with widths near 1 MeV were observed also in our previous work [10], where a part of experimental data on the ^{3}H(α, dα)n reaction was analyzed. The present work proceeds their more detailed consideration.

The three-particle ^{3}H(α, dα)n reaction in the kinematically complete correlation experiment was investigated on an isochronous cyclotron U-240 with the use of the beam of α-particles and titanium targets 2.7 mg/cm^2 in thick saturated with tritium. The ratio of atoms of titanium and tritium in a target was near 1. With the help of a specially developed procedure of measuring the energy and time characteristics of the particles accelerated by the isochronous cyclotron, it was revealed that the energy of α-particles in the experiment was equal to (67.2 ± 0.4) MeV [11, 12]. For the identification and measurement of the energy of charged products of the nuclear reactions, we used four $\Delta E - E$ telescopes. Two telescopes were positioned on the left side and the other two on the right side relative to the direction of the cyclotron beam. Two of them were intended for the registration of single-charge products of the nuclear reactions and consisted of semiconductor surface-barrier silicon detectors 400 μm in thickness and full-absorption detectors constructed on the basis of NaJ(TI) scintillators with ⌀20 mm×h20 mm. Another two were intended for the registration of double-charge particles and were consisted of ΔE and E semiconductor detectors 100 μm and 3 mm in thickness, respectively. In the experiment, we registered the events of binary coincidence between the pair of telescopes which were intended for the registration of single- and double-charge reaction products with the resolution time $\tau \approx 10^{-7}$ s. The parameters of every event (the amplitudes of analog signals from the ΔE, E detectors, time lag between moments of the registration of particles at different pairs of detectors — $t_i - t_j$, and the code of an event) were recorded on the magnetic disk of an SM 1420 computer in the form of a sequence of vectors for a further "off-line" statistical analysis.

We performed the energy calibration of the combined spectrometers with NaJ(Ti) scintillation detectors,

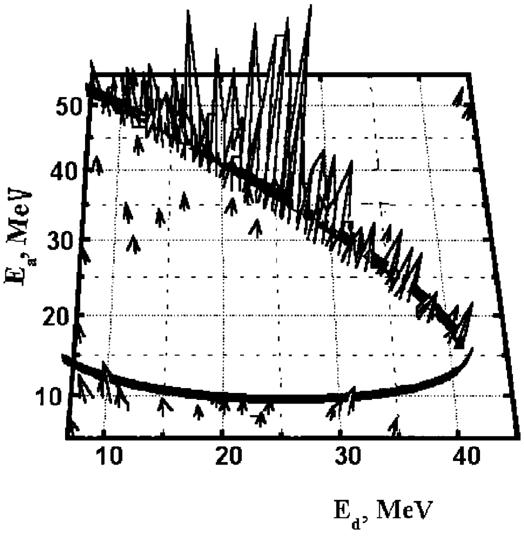

Fig. 1. The coincidence matrix

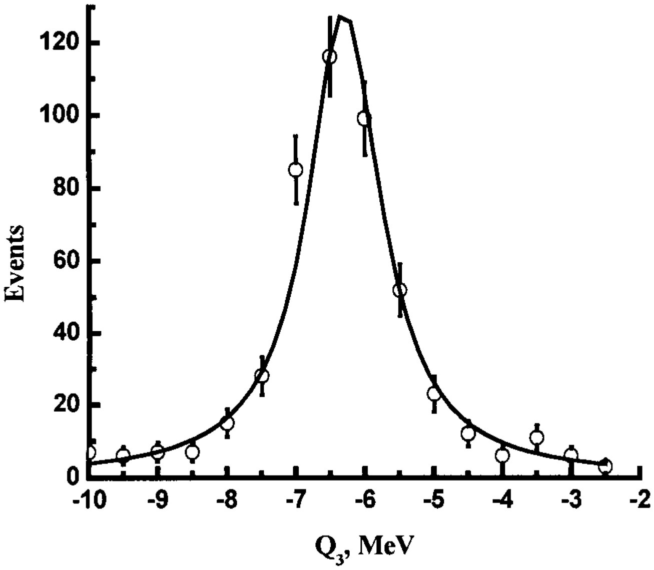

Fig. 2. Q_3 spectrum of the ^{3}H(α, dα)n reaction

whose response functions depend on the type of charged particles. Moreover, we developed and used the methods of simulation of the energy dependence of the light output of a scintillator on the specific ionization losses of the energy of a registered particle [12, 13]. As for the specific energy losses of charged particles in the matter, we used the relation $dE/dx \approx E^n/a$ [12, 14].

The "off-line" processing of the accumulated information consisted of both the sorting of experimental files with regard for the performed calibration of the spectrometers and the separation of events which corresponded to the registration of deuterons in one telescope and of α-particles in another one. By using the software package adapted for personal computers [15], we obtained the d—α coincidence matrices for 8 pairs of detection angles of deuterons and α-particles. In Fig. 1, we show one of the d—α coincidence matrices for the detection angles $\theta_d = 27.5^\circ$ and $\theta_\alpha = 15^\circ$. The solid line is a kinematic curve calculated for the relevant geometric conditions of investigation of the three-particle ^{3}H(α, dα)n reaction, whose arrangement relative to the experimental locus of coincidences testifies to the validity of the performed energy calibration. A more objective criterion of estimating a real precision of the determination of energy characteristics of the three-particle reaction is the value Q_3 which was obtained by recalculating the two-dimensional coincidence matrix into the one-dimensional spectrum Q_3 on the basis of the conservation of momentum and energy [16]:

$$\vec{P}_n + \vec{P}_\alpha + \vec{P}_d = \vec{P}_{\alpha 0}, \qquad (1)$$

$$E_n + E_\alpha + E_d + Q_3 = E_{\alpha 0}, \qquad (2)$$

where $\vec{P}_{n,\alpha,d}$ are the momenta of particles that take part in the three-particle reaction, $P_{\alpha 0}$ is the momentum of the incident particle, and $E_{n,\alpha,d,\alpha 0}$ are the relevant energies. With the help of Eq. (1), we estimated the kinetic energy of the third undetected particle, a neutron, and then we determined Q_3 from Eq. (2). In the case of a hypothetical experiment with the use of dotty (by size) detectors with absolute precision of determining the angle of their disposition and with the use of an infinitely thin target and a monochromatic beam of charged particles, this distribution would look like the δ-function with maximum which corresponds to the rated Q_3 of 6.25 MeV for the reaction ^{3}H(α, dα)n. But Q_3, being the spectrum calculated from the d—α coincidence matrix, looks in the real experiment like some distribution (Fig. 2). Indeed, the Q_3 distribution is determined by the exact formula (2), but the energies of particles in (2) are registered by real detectors with a certain energy resolution and a finite precision of the angle arrangement. Moreover, the beam of charged particles has the energy fuzziness and the angle dispersion. For the three-particle ^{3}H(α, dα)n reaction, we must observe a sole maximum in the case where all the three particles in the exit channel are created in the ground state. In Fig. 2, the solid line shows the approximation of the experimental spectrum by the Lorentz distribution with the use of the least-squares method. The curve has the maximum at 6.29(0.04) MeV,

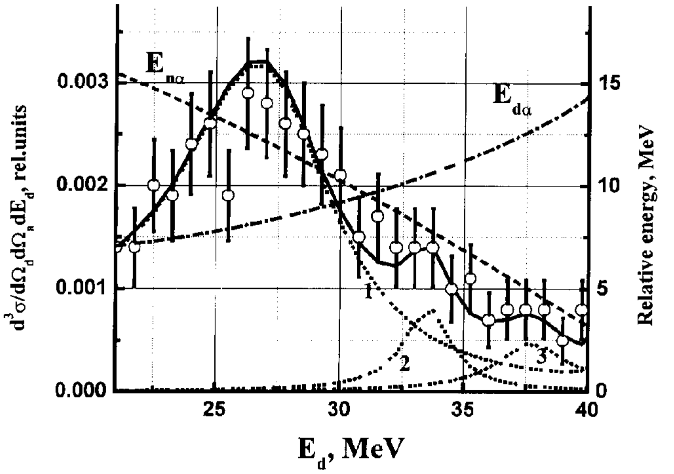

Fig. 3. Projection of the upper branch of the locus of the reaction on the deuteron energy axis for the detection angles of deuterons and α-particles, respectively, 27.5° and 15°. The dashed and dash-dotted lines are the relative energies in the α—n and d—α pairs. Solid line presents the results of approximation by (7), and dotted lines 1, 2, and 3 are the contributions of separate excited levels

which corresponds to Q_3 of 6.25 MeV for the reaction ^{3}H(α, dα)n. In this case, the distribution width equals 1.303(0.08) MeV and determines the total experimental absolute error of the correlation measurements.

Nuclear reactions with the formation of three particles in the exit channel can be predominantly viewed as processes with sequential two-particle interactions of different types: quasielastic scattering or quasi-two-particle reaction, interaction in the final state, and a sequential decay. The three-particle reaction ^{3}H(α, dα)n with creation of a deuteron, an α-particle, and a neutron in the exit channel can be treated as follows:

$$\uparrow \mathrm{d} + ^5\mathrm{He}^* \to \alpha + \mathrm{n}, \tag{3}$$

$$^3\mathrm{H} + \alpha \to \mathrm{n} + ^6\mathrm{Li}^* \to \alpha + \mathrm{d}, \tag{4}$$

$$\downarrow \text{quasifree } \alpha - \mathrm{d} \text{ scattering}. \tag{5}$$

Here, (3) and (4) correspond to the mechanism of sequential decay foreseeing the creation of the interim unstable system from two clusters (^{5}He*, ^{6}Li* in our case) at the first step which decays at the second step, (5) involves the process of quasifree α—d scattering appearing due to the virtual decay of the target nucleus, ^{3}H, into a deuteron and a neutron. In this case, it is necessary that the energy of the neutron-“spectator” be equal or be close to zero. In order to obtain a reliable information about parameters of the excited states of ^{6}Li, some experimental conditions should be satisfied. Namely, we should investigate that section of the phase space, in which the occupancy of certain levels of ^{5}He nucleus is kinematically impossible and the α—d quasifree scattering does not reveal itself. From eight pairs of the investigated registration angles of α-particles and deuterons for the three-particle ^{3}H(α, dα)n reaction at E_α = 67.2 MeV, the most optimal for studying the mechanism of creation and decay of the levels of a ^{6}Li nucleus with an excitation energy of 6 — 15 MeV were the pairs 15° — 15°; 27.5° — 15°; 21° — 15°.

For a further analysis of the experimental data, the d—α coincidence matrices for the chosen registration angles were projected onto the deuteron energy axis. In Fig. 3, we give the projection of the upper branch of the locus of the ^{3}H(α, dα)n reaction for the detection angles of deuterons and α-particles to equal, respectively, 27.5° and 15°. The calculated values of relative energies in the pair of particles d—α (the ordinate axis on the right) are marked by the dashed line. As seen from Fig. 3, the maximum in the spectrum is observed at the relative energies of 8.1, 10.5, and 12.6 MeV that corresponds to the excitation of ^{6}Li states with energies of approximately 9.6, 12, and 14 MeV, respectively. The confirmation of correctness of the choice of a section of the phase space, which corresponds to the creation of ^{6}Li nucleus with the excitation energy from 8 to 15 MeV, can be also obtained by analyzing the dependence of the relative energy in the α—n pair (the dash-dotted line in Fig. 3). It changes approximately from 5 to 15 MeV, which indicates the possibility of the formation and decay of excited levels of ^{5}He nucleus [see (3)] with excitation energies of 4.2, 7.2, and 11.7 MeV. But, according to the last compilation publication devoted to studying the schemes of the levels of light nuclei with $A = 5 \div 7$ [1], any levels are absent in this energy region for the excitation of ^{5}He nucleus. Therefore, we believe that just levels of ^{6}Li are excited. At the same time, such a pattern is also observed for the d—α coincidence matrices obtained for two other pairs of detection angles of deuterons and α-particles: 15° — 15°; 21° — 15°.

As known, the cross-section of a three-particle reaction can be presented as

$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE_1} = \frac{(2\pi)^4}{\hbar v_{\mathrm{in}}} |T_{if}|^2 \rho(E_1), \tag{6}$$

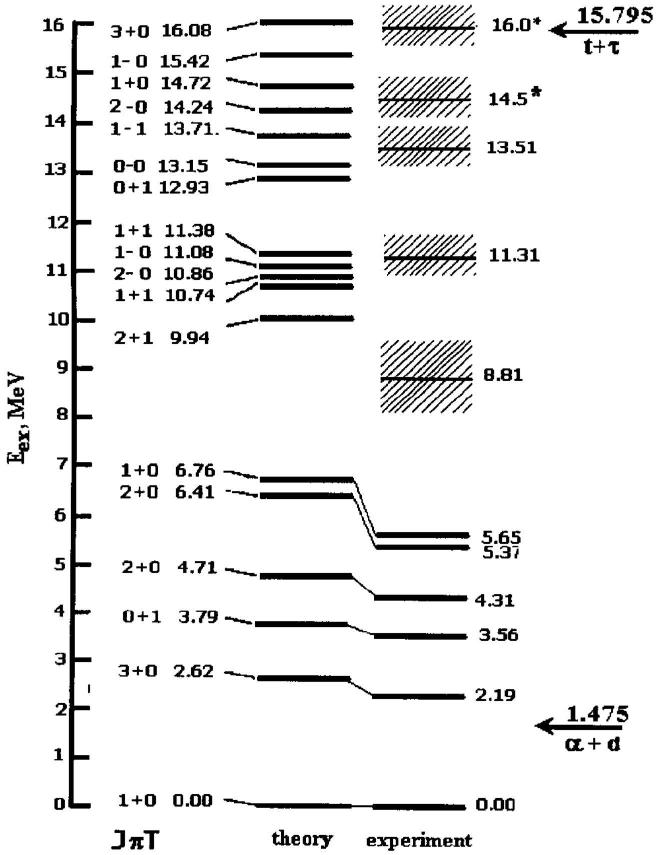

Fig. 4. Scheme of energy levels

where T_{if} is the transition matrix element, ρ describes the density of final states and is a factor related to the three-particle reaction phase space, and v_{in} is the relative velocity in the entrance channel.

For the ^{3}H(α, dα)n reaction, while supposing the sequential formation of ^{6}Li nucleus in the j-th state unstable to the decay into a deuteron and an α-particle, expression (6) becomes

$$\frac{d^3\sigma}{d\Omega_d d\Omega_d dE_d} \sim \rho(E_d) \sum_j^n C_j \frac{\frac{1}{2}\Gamma_j}{(E_{R_j} - E_{d\alpha})^2 + \left(\frac{1}{2}\Gamma_j\right)^2}, \quad (7)$$

where $\rho(E_d)$ is the phase space factor, E_{Rj} and Γ_j are, respectively, the energy position and width of the j-th excited state of ^{6}Li; C_j is the relative contribution of each resonance; $E_{d\alpha}$ — the relative energy in the d—α pair; and n is the number of excited states that are taken into consideration.

The experimental spectrum obtained as a result of projecting the upper branch of the α—d coincidence locus is approximated with the help of expression (7) by using the least squares method (Fig. 3). The results of approximation are given in Fig. 3 by the solid line. The dotted lines marked by numbers *1*, *2*, and *3* show the contributions of separate excited levels of ^{6}Li, whose energy positions and widths obtained from the fitting are: E_1 = 9.61(0.08) MeV, Γ_1 = 2.11(0.26) MeV; E_2 = 12.01(0.21) MeV, Γ_2 = 1.00(0.82) MeV; E_3 = 14.09(0.54) MeV, Γ_3 = 1.98(1.43) MeV. The same analysis was carried out for other chosen pairs of detection angles of deuterons and α-particles. As a result, we obtained the averaged values of the energy positions and widths and the errors of their determination: E_{ex} = 8.81(0.13); 11.3 (0.38); 13.51(0.38) MeV and Γ = 1.84(0.71), 1.28(1.09), 1.45(1.52) MeV, respectively.

Fig. 4 presents the scheme of ^{6}Li energy levels, on which the results of calculations obtained on the basis of the shell model modified for light nuclei [3] and the experimental values [1] are displayed. The averaged values of energy positions of the excited levels of ^{6}Li, obtained in this work with regard for the experimentally determined widths, are shown by the dashed lines, and the asterisk marks the levels which were observed earlier [10]. The derived new experimental data on the excited states of ^{6}Li agree with the theoretical calculations [3—7] and experimental investigations of other authors [8, 9].

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ДОСЛІДЖЕННЯ ЗБУДЖЕНИХ СТАНІВ ЯДРА ^{6}Li З ТРИЧАСТИНКОВОЇ ^{3}H$(\alpha, \mathrm{d}\alpha)$n-РЕАКЦІЇ

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Резюме

У кінематично повному експерименті з використанням пучка альфа-частинок з енергією 67,2 МеВ та титан-тритієвої мішені досліджувалась тричастинкова реакція ^{3}H$(\alpha, \mathrm{d}\alpha)$n. У верхніх гілках локусів (d—α)-збігів, отриманих для пар кутів реєстрації дейтронів та α-частинок 15°—15°; 27,5°—15°; 21°—15°, спостерігались три рівні ядра ^{6}Li в енергетичному діапазоні збудження від 7 до 15 МеВ. З підгонки, що базувалась на припущенні послідовного механізму реакції, на першому кроці якої відбувалось утворення незв'язаних рівнів ядра ^{6}Li, які в подальшому розпадались на d + α, отримано значення енергетичних положень $E_{\mathrm{ex}} = 8,81(0,13)$; 11,31(0,38); 13,51(0,38) МеВ та ширин $\Gamma = 1,84(0,71)$; 1,28(1,09); 1,45(1,52) МеВ відповідно для трьох резонансних рівнів, що спостерігались в експерименті.